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IIoT Based Multimodal Communication Model for Agriculture and Agro-Industries

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ABSTRACT The population would reach ten billion by 2050, and experts believe that the agricultural sector needs to boost production by 70% to satisfy the demand. Traditional farming practices rely on primitive technology that creates a yield gap with low productivity. A paradigm shift towards merging new technologies in the agriculture sector would enhance productivity, optimize cost, and encourage sustainable development. In this paper, we review the necessity for the fusion of the Fourth Industrial Revolution technological approach in the agricultural domain. We discuss the gap in supply chain management for the Industrial sector and Agricultural sector and identify the issues of vendor-specific production systems. We propose a multimodal communication model for the systematic integration of multi-vendor agricultural production systems. Our model utilizes the Data Distribution Service (DDS) middleware to enable communication between heterogeneous production systems to perform farming operations in a coordinated manner. Experimental work is conducted on a small-scale hydroponic farm to evaluate the system performance in terms of throughput, latency, and packet delivery ratio (PDR). The throughput for our proposed DDS system has significantly improved with the use of the BATCH QoS policy for payload size less than 1024 bytes. However, we incur an average latency of approximately 235 microseconds for any payload size. The value of PDR is 1 for any payload size ensuring our system to be reliable. The results suggest that our model can enable interoperability between multi-vendor production systems in real-time while incurring minimum latency.

INDEX TERMS Fourth industrial revolution, agriculture 4.0, agri-food industry, supply chain, IoT, IIoT, distributed system, middleware.

I. INTRODUCTION

Recent demographics predict population estimation to reach 10 billion by 2050 and 16.5 billion by 2100. As a consequence, the demand for food would escalate; agricultural production needs to increase by 70% to sustain this population growth. Currently, agriculture produces around 80-85% of food globally, but only 5% of the world's population works in agriculture. Agriculture accounts for approximately 70% of freshwater withdrawal and 90% of total water consumption worldwide. Moreover, urbanization leads to nutrition transition increasing processed food and meat consumption from 36.4 kilograms to 45.3 kilograms per person in 2030 [1]–[6]. A significant challenge faced by the agricultural sector is coping with the indeterministic weather conditions, deteriorating soil conditions, and negative environmental impact by farming practices. This sector needs to adapt to new technologies for enhancing productivity and efficiency to meet the food requirement of the increasing population. The prospective of future agriculture would provide social benefits such as food security as well as environmental benefits [7]–[9].

Agricultural processes are mainly crop and animal production, but mixed farming is gaining popularity due to its added advantages. Mixed farming is a combination of both arable farming and pastoral farming that can conserve the nutrient cycle in agriculture [10], [11]. With the advent of emerging technologies, agricultural operations would need to move away from the traditional methods and adopt new technologies that increase yield and production, reduce resource and post-harvest waste, recycle bio-waste and increase biodiversity [12]. Due to unpredictable weather patterns, reduced fertile land, and issues of agricultural infrastructure, we tend to move towards sustainable agriculture through the use of automation and digitization. The Fourth Industrial Revolution (Industry 4.0) [13], [14] will have a crucial influence on

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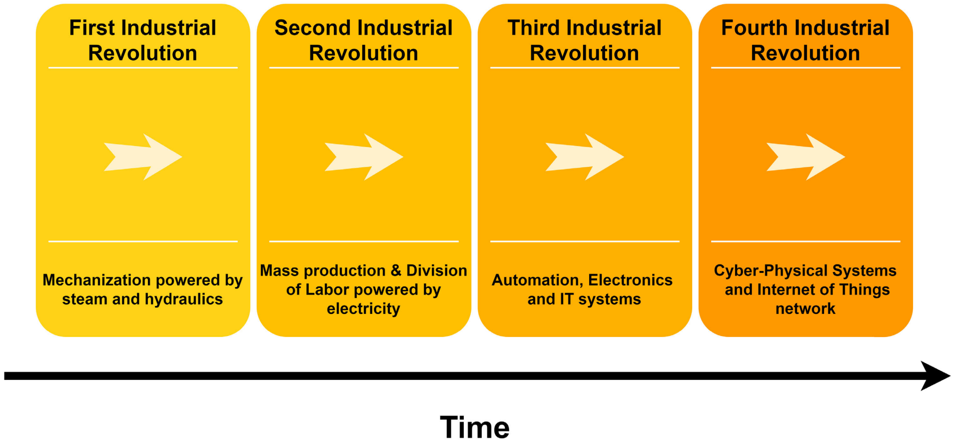

FIGURE 1. **Outline of industrial revolutions.**

the agricultural domain to scale and commercialize production [5]. The first industrial revolution began in 1760 with the invention of steam engines. With the discovery of the internal combustion engine, the second industrial revolution started around 1900. Eventually, this led to mass production with the use of oil and electricity. In the 1960s, the third industrial revolution started and characterized by the use of a programmable logic controller (PLC) [15] and supervisory control and data acquisition (SCADA) [16] systems to automate the manufacturing process. Hence industrial automation was first possible using electronics and information technology. The fourth industrial revolution, in 2011, transformed the industry integrating the cyber-physical system (CPS) [17], [18] and the Internet of Things (IoT) [19], [20] network to interconnect industrial production systems. Industry 4.0 provides greater versatility and more efficient resource allocation to optimize production and improve product life cycle [21]. Figure 1 outlines the industrial revolutions.

The foundational technologies [22] associated with the Industrial Revolution 4.0 are as follows:

- IoT and Industrial IoT (IIoT)
- Autonomous Robots
- Simulation
- System Integration - Vertical and Horizontal
- Additive Manufacturing
- Big Data and Analytics
- Cloud Computing
- Artificial Intelligence (AI)
- Augmented Reality
- Cybersecurity
- Drones
- Smart Sensors

Many of the above technologies are not recent innovations, but the application in the agricultural domain is limited. The advantages of incorporating Industry 4.0 approaches are improved productivity with lower production risks, bulk data collection for analysis, greater control over internal processes, and cost-effective. The most vital aspect of production in the industrial sector is the supply chain management [23], [24]. Therefore value creation in the agricultural domain must align with supply chain management. The uncertainty in farming supply chain management is due to the unpredictable weather and environmental (soil and nutrient dynamics) conditions [25]. This complexity in the agricultural domain makes experience-based heuristic methods appropriate. Existing approaches in farming supply chain use data-driven technologies such as precision agriculture to increase yield, reduce pest and disease infestation, and optimize resource usage. Other technologies, such as Bluetooth, Global Positioning System (GPS), and radio frequency identification (RFID), enable communication between machinery and systems to produce optimized, interconnected, and independent production systems. With Industry 4.0, we need to rethink the concept of supply chain and manage system integration. The main idea is the merging of the real-world environment and digitalized systems along whole agricultural supply chains. Emergent technologies, such as the IoT, Cloud Computing, Robotics, and AI, have the potential to progress to the next agricultural revolution [26]–[30].

Agriculture 4.0, that advanced from the Green Revolution (Third Agricultural Revolution) [31], uses system integration and coordination between farming activities. Agriculture 4.0 will have to balance between demand-side and the supply chain value side of the food-scarcity equation, using technology to improve and address the real concerns of the value chain. The tools and machinery in the farming environment have advance embedded technology, which allows automation and real-time communication with interlinked production systems. The use of robotics, AI, cloud computing, and big data analytics would further boost overall productivity, improve sustainability, and reduce the yield gap. Nonetheless, planning and control can be inconvenient due to the high mobility of production plants and inconsistent communication. Agricultural activities can be sequential or parallel, thereby requiring a highly coordinated system. A crucial aspect in the area of supply chain management is the ability

TABLE 1. Design principles of Industry 4.0.

Principle	Advantages
Interoperability	Increased machine life cycle, Cost reduction, Increased portability Greater collaboration
Decentralization	Greater flexibility, Higher availability and autonomy, Efficient resource utilization, Fault-Tolerant
Virtualization	Reduced industrial waste, Increased recycling opportunities, Encourage sustainable environmental practices
Real-Time Capability	Efficient resource usage, Faster response to changes, Easier adjustment to demand curve
Modularity	Improves manageability, Increased reusability, Easy detection of issues, Reduced cost
Service Orientation	Increased reusability, Reduced resource and energy consumption, Decreased waste

to coordinate activities. Industry 4.0 relies on the concept of independent CPSs to reliably communicate with each other and achieve a high level of coordination. Table 1 displays the design principles [32], [33] that govern the Industry 4.0.

The vision of Agriculture 4.0 is considerably limited to the application of precision farming and automation. This limitation is due to the use of distributed vendor-specific production systems in the agro-industry. The increased degree of complexity with heterogeneous production systems can render the agro-industry inoperable. We propose a multi-modal communication model for the agro-industry to integrate these multi-vendor production systems. The objective of our research is to introduce a model that allows interoperability and adaptability between production systems in a heterogeneous environment in real-time. The rest of the paper is structured as follows: Section II reviews the literature survey comprising the approaches taken in agriculture and agro-industry. Related terminologies and their applications in the smart agricultural systems are highlighted in Section III. Section IV provides an overview of the real-time distributed systems and DDS model and architecture. Our proposed communication model is presented in Section V. Section VI describes the experimental work carried out for our study, followed by results discussion in section VII. Finally, in section VIII, the conclusion and future work are discussed.

II. LITERATURE REVIEW

Traditional agricultural methods are not adequate to meet the population demand. Due to the unpredictable weather and environmental conditions, farm producers are shifting towards Wireless Sensor Network (WSN) and IoT based smart farming systems to enhance productivity and efficiency while reducing negative impacts on the ecosystem. Several prominent studies have been carried out by various research groups in the agriculture domain [34], [35], and details of a few works have been presented in this section. Developments in the communication network infrastructures and technologies have led to the integration of modules in WSN that provide connectivity between nodes and change network topology from centralized to distributed infrastructure. The authors of [36] designed an automated variable rate irrigation system that allows remote monitoring and control of a site-specific irrigation system using a distributed wireless sensor network. The proposed system consists of an in-field sensing station that periodically monitors the environmental conditions, an irrigation control station that controls remote sprinkler head valves, and a base station that processes the data. In-field sensed data, along with data from weather stations, are transmitted to the base station wirelessly. The graphical user interface was developed for real-time monitoring and control and implemented using wireless in-field sensing and control (WISC) software, which was elaborated in [37]. The base station calculates the watering instructions based on the in-field data and sends control signals to the nozzle controller to automate the irrigation process.

In [38], the authors presented an autonomous device to optimize water usage in agriculture using wireless sensor nodes with GPRS connectivity. The system design consists of an electronic board (main-board), sensor-board, and GPRS-board. The configuration information is loaded during bootup, and the main-board defines the sampling time, rate of transmission, server configurations, and GPRS settings. The crop and environmental data are collected by the external sensors, which are interfaced to the sensor-board and transmitted to a remote storage server via GPRS-board for further analysis. The system is implemented following a client-server architecture, which can serve as a bottleneck when the number of sensor nodes is increased. A computer-based vertical hydroponic system was developed by Rius-Ruiz *et al.* [39] that analyzes and calculates the optimum low-cost nutrient solution for tomato plants. The authors of [40] proposed a reliable control system to cultivate tomato plants hydroponically using a different frequency band on the IEEE standard protocol. Wireless sensor nodes measure the environmental parameters in real-time and send the aggregated data to the system via a gateway. Based on the temperature, light intensity, and humidity readings, the proposed hydroponic control system calculates evapotranspiration. If the value exceeds a certain threshold set by the user, then control signals are sent to the actuator system that controls the flow of nutrients. The authors believe their system to be fault-tolerant and acknowledge the existence of scalability issues. Nevertheless, both works do not track or automatically manage all the required parameters for agricultural production. Also, the system is not suitable for large size of data.

There have been tremendous advances in sensing and network technologies that enable multiple sensors to connect and integrate for real-time management of the farm. For the development and implementation of IoT solutions, embedded devices like microcontrollers and single-board computers have been used. An automated IoT-based connected farm was introduced in [41] for growing and monitoring crops. The proposed system can integrate multiple farms which can support several IoT devices. The three main components are the physical devices, &Cube, and Mobius. The physical devices are the sensors and actuators that monitor and measure the environmental parameters. &Cube is the software platform deployed on the IoT gateway for enabling connectivity of devices to the connected farm. Mobius is an oneM2M compliant IoT service platform that facilitates the monitoring and controlling of the connected farm. Any IoT device can connect to Mobius via &Cube through registration. The users can monitor and access the farm data via web or mobile application using RESTful API interfaces implemented on the Mobius. The authors implemented the proposed farming system and mobile application to test the feasibility. Also, service scenarios are described to highlight the advantages of a connected farm. However, considering the heterogeneity of existing communication devices and protocols, it lacks versatility.

The authors of [42] proposed a ubiquitous sensor network platform using IoT technologies to integrate heterogeneous machines, monitor and control crop growing systems for precision agriculture. The three elements of the proposed platform are Things, Local Gateway, and Network and Cloud. These elements are distributed into four layers and use the Message Queue Telemetry Transport (MQTT) protocol and RESTful API as the communication paradigm. Experimental work was conducted using embedded devices, such as Raspberry Pi, and sensor networks on a hydroponic station within a greenhouse. The authors concluded their system to be cost-effective and lower water usage. However, there is a lack of versatility in this proposed method, and the use of gateway could give rise to scalability issues. Kamruzzaman *et al.* [43] developed an IoT-based device for smart farming to monitor and control environmental factors that affect crop production. Sensors to measure soil and atmospheric conditions are interfaced with a microcontroller, and the aggregated data is transmitted to a remote server via a WiFi module. A data analysis and prediction algorithm called autoregressive integrated moving average (ARIMA) is implemented to predict future environmental conditions for better growth. The authors do not consider the integration of several heterogeneous IoT devices in the system. Also, it followed the client-server communication paradigm that can act as a bottleneck when more number of IoT devices are integrated into the system.

IoT networks can consist of heterogeneous devices, and one key challenge is the interoperability between them. Recent research on sematic interoperability allows system integration using the Web of Things (WoT) [44], [45]. Touseau *et al.* presented ASAWoO [46], a WoT based middleware platform, to integrate heterogeneous cyber-physical objects using Avatars in a farming environment. It employs WoT technologies for interoperability between objects and uses opportunistic networking, an extension of the Delay-Tolerant Network (DTN), for connectivity between physical objects. The physical objects, controlled through Avatars [47], [48], monitor and manage environmental conditions at the farm. Avatars functionalities are implemented as REST services, which are invoked using Hypertext Transfer Protocol (HTTP) and Constrained Application Protocol (CoAP) application-level protocols. The authors validated the proposed platform by deploying it on single-board computers (Raspberry Pi) to act as physical objects on an experimental farm. The Avatars hide device heterogeneity, and the platform implemented as a loosely coupled client-server architecture ensures monitoring of the farming environment in real-time. Although this platform can be beneficial when there is no network infrastructure, numerous data exchanges and highly mobile objects can make it less efficient.

The authors of [49] intorduced an IoT-based water management system for monitoring water consumption in real-time at smart agricultural farms. The system has microcontrollers integrated into the nodes and gateway for balancing between accuracy and energy efficiency. Detailed schematic diagrams of the components are presented as a design objective. The sensor nodes have external sensors interfaced to the microcontroller to measure the soil moisture, temperature, humidity, rain, and water level. The measured environmental data is sent to the cloud or mobile application via the gateway using LoRa and WiFi modules. The experiments conducted show the feasibility of the system in tunnel farming. The authors believe their system to be cost-effective, achieving higher productivity and flexibility to manage multiple independent farms. The authors did not address the data packet loss in the proposed application. Also, efficiency might reduce when more nodes are needed.

Triantafyllou *et al.* [50] proposed a remote sensing reference architecture model that employs IoT and WSN technologies for monitoring smart farming systems. The model components are distributed similarly to the OSI Model into seven layers, namely Sensor Layer, Link Layer, Encapsulation Layer, Middleware Layer, Configuration Layer, Management Layer, and Application Layer. The sensors and smart embedded devices to measure and monitor environmental parameters reside in the Sensor Layer. The Link Layer composes the network and routing technologies between sensors for data transfers. The encapsulation of the in-field measured data takes place in the Encapsulation Layer to connect to the internet. The Middleware Layer interconnects heterogeneous IoT nodes or devices using application-level transport protocols. This layer is responsible for the interoperability of different devices and their underlying protocols. The Configuration Layer is responsible for data aggregation, organization, and publication as context information. The Management Layer processes and analyzes the collected data based on data mining or management methods. The application module for users resides in the Application Layer. The authors present a use case study based on the DIAS project to understand the proposed architecture model. However, this work did not consider the communication mechanism between the seven abstraction layers, and no real implementation was carried out and discussed.

In [51], the authors proposed an autonomous sensor network to monitor and control irrigation systems for rural agriculture environments. The prototype developed is suitable for small or medium-sized farms. The system consists of sensor nodes, a coordinator node, and a cloud platform. The sensor nodes are microcontrollers (Arduino NANO) with external sensors, actuators, and the Zigbee module interfaced for communication. Environmental parameters such as temperature, light, humidity, and rain levels are measured and aggregated data sent to the coordinator node using Zigbee protocol for communication. The coordinator node consists of a microcontroller (Arduino Mega ADK), WiFi module (ESP8266), and Zigbee module. Local weather information can be accessed using the weather forecast API. The received sensor data is sent to the cloud platform using MQTT as the communication protocol. The users can visualize information and control the watering system remotely. The authors believe their system to be cost-effective with the capacity to self-charge. However, the authors did not perform in-field extensive experiments to validate system performance.

The evolution of IoT in the agricultural sector will incorporate IoT technologies in different production systems to enable automation. With automation in farming operations and machinery, modern agriculture directs towards becoming more industrialized to fulfill future food production demands. The authors of [52] introduced Ipanera, an IoT-based platform to control water quality in a distributed aquaponics system using Industry 4.0 technologies. The system architecture consists of endpoints with adaptive fuzzy logic controllers, analytical and web servers, and an IoT cluster. The authors believe that their platform would integrate and adapt multiple soil-less food production systems to automate and control the water quality. However, the authors did not carry out any experimental work to validate their proposal. The stages of agricultural food production systems require a balance between the supply chain and the value chain. Industrial Internet of Things (IIoT) technologies promote the automation of production systems and enable food traceability [53]. Agricultural logistics interconnect producers and consumers to trace the whole production process [54]. Pang *et al.* [55] proposed an IoT-based value-centric framework to trace the food production supply chain. Sensor portfolios are derived from value creation, availability, and cost assessment analysis to track and monitor production logistics. The authors implemented a prototype to check the feasibility of their proposed system. However, the authors did not consider reliability and connectivity issues in WSN.

Most of the existing research uses a centralized client-server communication pattern, which becomes a single point of failure. Also, the addition of more IoT devices can act as a bottleneck, degrading system performance. IoT systems are highly distributed, with the devices being characteristically heterogeneous. This heterogeneous nature gives rise to interoperability and connectivity issues. There is a lack of integration between heterogeneous systems that can make it inconvenient to expand businesses with different IoT devices. Integration of legacy proprietary systems into modern farming systems is difficult due to interoperability issues. These studies do not tackle the challenges of incorporating IIoT technologies in the agricultural domain, as mentioned in [56], [57]. Few works used the MQTT protocol, which follows a broker based publish-subscribe pattern. Although it solves the interoperability issues, the system suffers from centralization problems with a single point of failure reducing performance. Furthermore, none of the works in the literature consider the different Quality of Service (QoS) requirements of production systems. Therefore, from a careful examination of existing studies, we concluded that there is a requirement for a communication model to integrate multiple modular heterogeneous production systems. Our proposed model would enable horizontal and vertical integration of modules while ensuring reliability and versatility. Interoperability between systems would automate the production process enhancing productivity and efficiency.

III. RELATED TERMINOLOGIES

Various techniques have been adopted by researchers and practitioners to enhance productivity and efficiency in agriculture. Related terminologies and approaches are discussed in details in this section.

A. INTERNET OF THINGS AND WIRELESS SENSOR NETWORKS

The authors of [58] proposed a context-aware middleware, that uses ontology model for context representation, to provide abstraction of the collected data from ubiquitous greenhouses and process or filter the data depending upon the services intended to be received by the user. For performance evaluation, the proposed middleware was integrated with the management system in the greenhouse. Soil and environmental sensors were deployed in the greenhouse as well as CCTVs were installed to acquire all the data produced from the greenhouse. The environmental parameters were controlled using ventilation system, irrigation system etc. that are in turn controlled through a PLC. The proposed system was tested by measuring CPU usage and response time and the authors believed it to be practical.

Zamora-Izquierdo *et al.* [59] proposed and developed a platform that incorporates automation, IoT technologies, edge and cloud computing to monitor and manage the closed hydroponic system with recirculation using saline water. The proposed system architecture has been divided into three planes namely local CPS plane, edge plane and cloud plane. The CPS plane is responsible for atomic decisions taken by CPS nodes after it gathers data from sensors. The main precision agriculture tasks are managed in the edge plane where CPS nodes communicate using MQTT [60], [61] or CoAP [62], [63]. The cloud plane performs data storage and analysis. It maintains communication with the system using Next Generation Service Interface. The authors implement the proposed platform in a real greenhouse environment and conclude that their system is reliable and cost-effective in semi-arid conditions.

The SheepIT project [64] was introduced to develop an IoT-based autonomous solution for monitoring and condition the sheep's posture and location in vineyards. The details of the requirements of the SheepIT project was discussed in [65]. The system architecture composed of two modules namely WSN that included set of mobile nodes and beacons to perform local functions of the system and Computational Platform (CP) that provided data storage and data analysis for the user [66]. The proposed stack consisted of four layers (Physical Layer, MAC Layer, Transportation Layer and Application Layer) and are described in details in [67]. In [68], the authors reviewed the proposed stack and focused primarily on the design and development of the gateway connecting the two modules, WSN and CP. The gateway apart from forwarding data between the two modules support few real-time critical functions such as raising alarm in case of emergency, perform on-site administrative tasks and enabling technical interruptions. The performance of the gateway was evaluated in a real scenario and authors concluded the proposed system to be feasible and scalable.

B. MACHINE LEARNING AND DEEP NEURAL NETWORKS

The adoption of artificial intelligence and machine learning techniques have enhanced productivity and eased the decision process in the agricultural industry. Machine learning algorithms and automatic classification techniques are more effective in the detection and monitoring of crops or livestock than manual methods. Seed classification is vital for seed harvesters to ensure the quality of the product. The research in [69], [70] proposes the use of machine learning and ant colony optimization algorithms, and data mining techniques to classify seeds more accurately.

Frost events in farmland can be harmful for crops and can affect the production of goods [71]. The peach project in [72] proposed using IoT technologies in predicting frost events in orchards. The authors deployed a low-power dense mesh network with sensors to collect data and predict the frost events. The authors of [73] extended this work by applying appropriate machine learning algorithms to predict the frost events with fewer errors and more sensitivity. There are three stages involved in predicting frost events and the authors mainly focused on the second stage which is training the frost-prediction engine using machine learning algorithms. They proposed to use Bayesian networks (BNs) [74] and random forest (RF) [75] for regression and logistic regression and binary trees for classification. The samples were generated using synthetic minority oversampling technique (SMOTE) [76]. Also, thermodynamic information of neighboring location has been used to improve the accuracy of the prediction.

IoT based hydroponic system using Deep Neural Networks [77] proposed by Manav Mehra *et al.* implemented Deep Neural Network (DNN) at the edge for controlling the parameters of the hydroponic system and at the cloud for classifying the control action based on the parameters collected. Parameters such as pH, temperature, humidity, water level and light intensity are measured by sensors in real-time and sent to the microcontroller. The single-board computer acts as the edge where the DNN model is implemented and trained from the cloud based on the data set. The predicted output based on the DNN model is then communicated to the microcontroller for the appropriate action to be taken. A case study for the growth of tomato plant was conducted using the developed prototype and results showed an accuracy of 88.50%.

Mark F. Hansen *et al.* [78] presented three face recognition techniques in order to identify the individual pigs on the farm. A webcam was placed on the drinker connected to a laptop to collect digital images of the pigs. The collected image data undergoes structural-similarity index measure (SSIM) [79] to remove similar data. The authors proposed using convolutional neural network and a fully connected layer for feature extraction and classification. The proposed algorithm identified pigs based on three regions namely snout and wrinkles above snout, marking on top of the head and eye regions. It was compared against Fisherfaces [80] with Euclidean distance and VGG-face pre-trained Convolutional Neural Network [81] with linear support vector machine (SVM) for face recognition. The authors concluded that their proposed algorithm is feasible and provides an accuracy of 96.7%.

C. DRONES

The term "Internet of Drones (IoD)" was first coined in [82], presenting the conceptual architecture to tackle the drone airspace management problem along with defining new terminologies and goals of the proposed model. Nayyar *et al.* [83] introduced the concept of the Internet of Drone Things (IoDT), including the associated technologies, challenges, and applications. The authors also highlighted some real-time implementations in smart agriculture and smart city domains. In [84], the authors presented an end-to-end IoT platform for precision agriculture with the help of sensors and drones. The proposed platform ensures connectivity and availability even during power and Internet outages. The system architecture consisted of four modules namely sensors and drones, IoT base station, IoT gateway and cloud service. The authors proposed a weather-aware IoT base station that ran on solar energy and the different components are duty cycled based on the weather forecast and charge state of the batteries. The IoT gateway provided local functions in the farm and also summarized the collected data to be uploaded to the cloud. The authors also incorporated a path planning algorithm and yaw control algorithm for the drone to optimize the energy consumption and extend the battery life of the drones. In addition, the generation of the precision map from drone and sensor data have been implemented. The proposed system was deployed in two farms and each components have been evaluated in terms of power, time and accuracy.

In [85], the authors discuss the use of AR drones for irrigation in the agricultural domain and propose to implement Optimized Link State Routing Protocol (OLSR) [86], [87] to route the information between devices in an ad hoc network. To enhance the video sensing and transmission quality, they integrated Real Time Streaming Protocol (RTSP) [88] and Real-time Transport Protocol (RTP) [89], [90] protocols in the system. In another variation [91], the authors propose using multiple AR drones forming mobile ad hoc network (MANET) for intelligent video sensing to deploy herbicide sprayer based on a geo-reference system. They believe the system can save the amount of herbicide used, and the quality of the crop is improved.

A distributed swarm control algorithm was proposed in [92] to allow control of multiple Unmanned Aerial Vehicle (UAV) systems used for agricultural purposes. A single operator can remotely control the multi-UAV system using control inputs such as velocity control, formation control, and collision avoidance control. The system has two layers, the UAV control layer that manages the formation of multiple UAVs and the teleoperation layer that controls the motion and velocity of the UAVs. The authors implemented the proposed algorithm using a robot operating system and Gazebo to validate and evaluate the control algorithm. They concluded that the proposed distributed control algorithm is more efficient than a single UAV system. The added advantage of utilizing DDS middleware for communication between multiple UAV systems are presented and discussed in [93], [94].

D. CYBER SECURITY

An attacker can discover new methods to infiltrate the IoT based farming systems, raising new security and privacy concerns that require better security mechanisms to tackle the issues in communication [95]. To protect against false data injection attacks, the authors of [96] proposed a Lightweight Privacy-preserving Data Aggregation (LPDA) system to aggregate fog-computing data from hybrid IoT devices at the network edge by applying homomorphic Paillier encryption [97], Chinese Remainder Theorem, and one-way hash chain. Security analysis using differential privacy techniques [98], [99] implied the proposed scheme to resist against differential attacks. The proposed technique was evaluated against Aggregation with the Basic Paillier Encryption (AggBPE) in terms of communication overhead and computational cost, and the experimental results indicated it to be lightweight for fog-computing nodes.

The use of RFID technology in agriculture is growing significantly, from monitoring and tracking cattle to use in food traceability systems [100], [101]. Due to privacy and security concerns, the authors of [102] introduced an anonymous lightweight RFID authentication system for distributed IoT environments using hash functions. The proposed system architecture included an authenticated cloud server, a back-end database server for each RFID network, and clusters containing readers and RFID-tags. The proposed authentication scheme had three phases and used hash functions. Although false data injection and distributed denial-of-service attack (DDoS) attacks are not considered, the proposed system can protect against cloning attacks, replay attacks, forgery attacks, and location tracking attacks as described in functional and security analysis. In [103], the authors introduced a security model to allow secured data communication independent of the network infrastructure using symmetric and asymmetric cryptographic algorithms, digital signature, digital envelope, and public key infrastructure (PKI). The authors believe their proposed scheme can ensure data security but consume more energy due to the inclusion of authentication overhead.

E. AUTONOMOUS TECHNOLOGIES

Automation technologies in the agricultural industry have made farms more productive and automate the production cycle of crops or livestock. With the development of autonomous vehicles, farming operations need to consider the entire production system to enable a high degree of automation. While these innovations are recent, a growing number of agricultural businesses have been implementing field automation in their industrial processes. The EU-project CROPS [104] developed a modular and reconfigurable agricultural robot to perform agricultural tasks such as monitoring, spraying, and harvesting. In [105], the authors studied the detection of powdery mildew in grape vineyards and the application of pesticides to control the disease using the robot developed by CROPS. The proposed system automatically identified the disease and applied spray while reducing the amount of pesticide used.

The authors introduced an autonomous Agricultural Robot (AgBot) System [106] that can detect weeds using Haar feature-based cascade classification and spray a controlled amount of herbicide or fertilizers while navigating using GPS. In [107], the authors proposed a solution for the connection between the autonomous vehicle and spray management system to perform spraying operations autonomously in the field. The architecture comprised of four subsystems, namely, mobile tracking robot, localization and navigation system, smart spraying system, and human-machine interface (HMI) system. The performance of the system was evaluated in the greenhouse and vineyard scenario, and results indicated that the autonomous vehicle followed the desired trajectory. The authors believe their proposed system can expand by incorporating other applications using this approach. Other automation advances in greenhouse technology and controlled environment agriculture (CEA) are discussed in detail in [108].

Most of the research implements Industry 4.0 technologies in their systems to enhance productivity or reduce cost without taking into account the possibility of heterogeneous vendor-specific production systems. The communication between these production systems needs to be homogeneous. Hence we tend to propose a communication model that

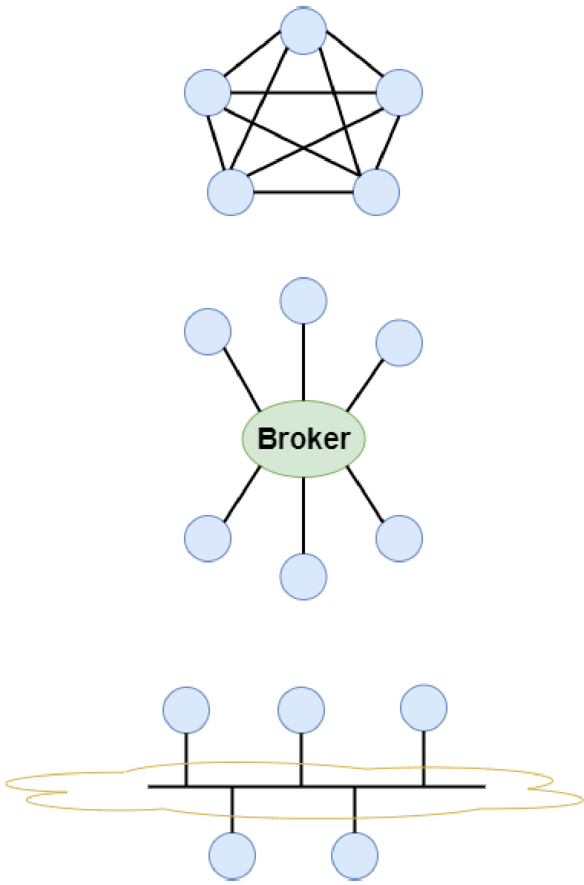

FIGURE 2. Integration approaches for distributed systems.

will integrate these production systems. The proposed model relies on DDS middleware [109] discussed in the following sections.

IV. BACKGROUND

A. REAL-TIME DISTRIBUTED SYSTEMS

A distributed system is a group of autonomous devices that interact and coordinate through a network. The integration approaches shown in figure 2 for a distributed system are as follows:

- Point-to-point (application-centric)
- Centralized
- Distributed (data-centric)

The point-to-point approach is tightly-coupled with high life-cycle costs, difficult to maintain, poor information sharing, and robustness. Centralized integration relies on the broker hence resulting in low scalability and performance with a single point of failure. On the other hand, the distributed integration approach has high throughput with low latency, high scalability, high reliability, integration logic is vendor-independent, robust, and high availability. Due to these advantages, DDS follows a distributed integration approach. Real-time systems are time-constrained systems where expected response time can be assured. Their classification is of three types, which are explained as follows with the help of figure 3. In figure 3, e_1 and e_2 represents two consecutive events in time.

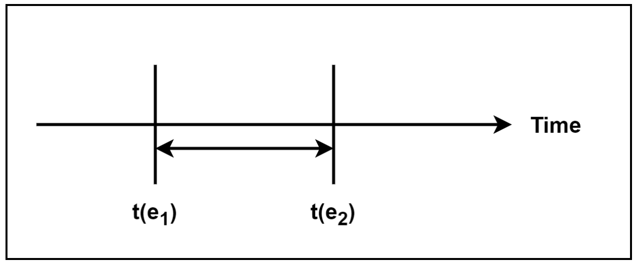

FIGURE 3. Timing constraint diagram for real-time systems.

- **Hard Real-Time**: The timing constraint is defined as a point of time i.e. $t(e_1) = t(e_2)$.
- **Soft Real-Time**: The timing constraint is defined as a window of time i.e $t(e_1) < \mathrm{t} < t(e_2)$. Acceptable time window but can be flexible by few seconds.
- **Firm Real-Time**: The timing constraint is defined as a strict window of time i.e $t(e_1) < \mathrm{t} < t(e_2)$. Time window is strict and delays are not acceptable.

B. DATA DISTRIBUTION SERVICE

The Object Management Group (OMG) introduced DDS in 2004, an open data-centric standard, to address the communication challenges of real-time mission-critical applications with the issue of scalability in mind [110]. This specification standard intends to integrate heterogeneous systems enabling interoperability and portability. The purpose of the DDS specification is to allow the sharing of information efficiently in a distributed environment masking the underlying complexities [111]–[113]. The specification standard is composed of the DDS application programming interface (API) and Data Distribution Service Interoperability (DDSI) wire protocol. There are two interface levels specified in the DDS API standard, namely Data-Centric Publish-Subscribe (DCPS) and Data Local Reconstruction Layer (DLRL). The lower DCPS layer deals with topic-based data dissemination using the publish-subscribe paradigm. This layer aims to provide an efficient delivery mechanism between the Publishers and Subscribers. The higher layer, DLRL, is responsible for allowing the integration of DCPS components into the application. This layer is optional and helps application developers to create an object model above the DCPS layer hiding the underlying DCPS information. Real-Time Publish Subscribe (RTPS) is the standard DDSI wire protocol that ensures interoperability between the various implementations of the DDS standard [114]–[116]. DDS also encompasses a rich set of QoS policies that control the communication behavior and properties of information. The model of DDS relies on the concept of a fully distributed Global Data Space (GDS) in which participants can either publish or subscribe to data. Due to the decentralized implementation of GDS, there is no single point of failure or bottleneck that might degrade the performance. A domain is a single GDS instance

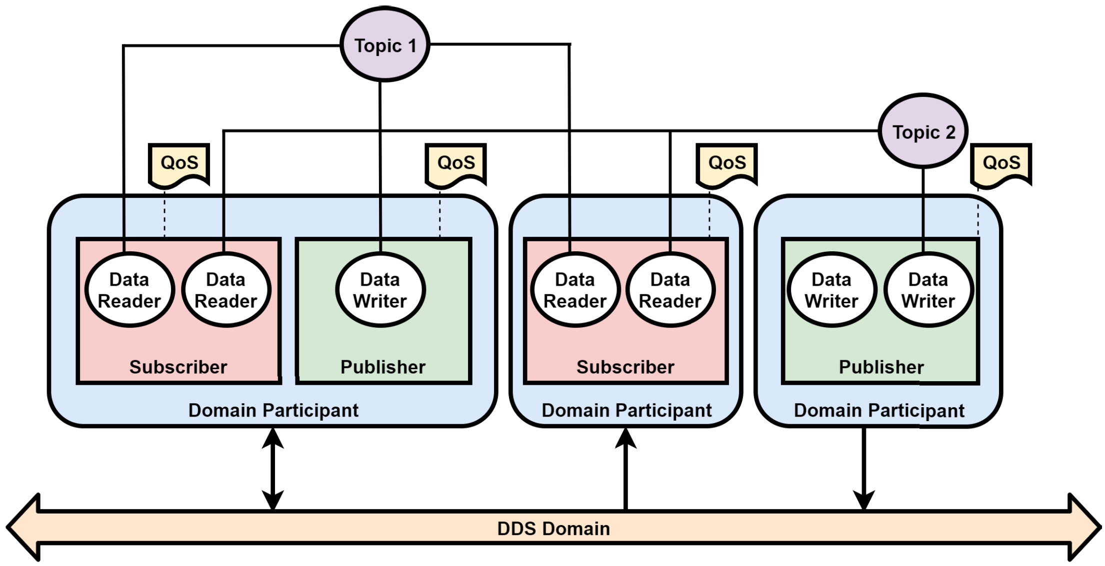

FIGURE 4. Architectural representation of data distribution service model.

uniquely identified by domain ID. As shown in figure 4, the DDS Entities belonging to a particular DDS domain are as follows:

- **Domain Participant**: It represents the joining of an application to a specific domain. A single application can join multiple domains by creating multiple domain participants with different domain IDs. DDS Entities are contained and managed by the domain participant.
- **Topic**: Topic is defined as a 3-tuple Entity composed of a unique name, type, and QoS parameter. It is associated with a unique key to distinguish a topic instance. Samples are updates of topic instances that are produced or consumed by the Publisher or Subscriber, respectively. Topic types can be specified using Interface Definition Language (IDL), eXtensible Markup Language (XML), Unified Modeling Language (UML), or annotated Java.
- **DataWriter**: This Entity generates samples of one or more instances of a topic with a given QoS. It is associated with the Publisher to write data to the GDS. A single DataWriter is owned and managed by one Publisher only.
- **DataReader**: It consumes samples of one or more instances of a topic with a given QoS. It is associated with the Subscriber to read data from the GDS. A DataReader can store multiple samples in the cache based on the QoS setting. A single DataReader is owned and managed by one Subscriber only.
- **Publisher**: The Publisher is the Entity that is responsible for publishing data with a given QoS. It can send data for several different topics with different data types. Multiple DataWriters are owned and managed by a single Publisher.
- **Subscriber**: This Entity is responsible for receiving the published data in the GDS with matches QoS. It can read data for numerous different topics with different data types. Multiple DataReaders are owned and managed by a single Subscriber.

Domain participant nodes in the GDS are either a Publisher, Subscriber, or both. A Publisher encloses one or more DataWriters, whereas a Subscriber contains one or more DataReaders. These DataWriters and DataReaders will be automatically discovered and matched to other participants with similar properties establishing connections. Adaptive connectivity enables a Publisher or Subscriber to join or leave the DDS domain at any given time. Active participants in the GDS are discovered by the Participant Discovery Protocol (PDP) that exchange information and establish endpoints using the Endpoint Discovery Protocol (EDP) [117]. The communication behavior of the system relies on a set of configurable parameters specified in the QoS policies, as shown in Table 2. Each policy governs a particular aspect of Entity behavior, which can be configured using QoS parameters to ensure reliable and efficient communication. Due to the fully distributed nature of DDS, the standard offers incredibly high levels of efficient abstractions to create and integrate distributed modular systems on a large scale. Therefore, we tend to utilize the concept of DDS in the agricultural domain.

V. PROPOSED MODEL

In our study, we introduce a novel multimodal communication model to integrate real-time farming production systems in a heterogeneous environment. The proposed model uses a distributed integration approach along the agricultural supply chain. Our model uses the DDS specification standard by OMG that enables the communication between the different automation layers of agro-industry production plants. Figure 5 depicts the proposed multimodal communication model that is tailored to the requirements of the agro-industry.

TABLE 2. Quality of service policies governing data distribution service behavior.

Quality of Service Policy	Purpose
USER_DATA	The generated Entity object's additional information is specified by this policy.
TOPIC_DATA	The generated topic's additional information is specified by this policy.
GROUP_DATA	The generated publisher's or subscriber's additional information is specified by this policy.
DURABILITY	The durational existence of the published data samples is determined using this policy.
DURABILITY_SERVICE	The configuration of the DURABILITY service is indicated by it.
PRESENTATION	The representation of the samples to the subscriber is defined using this policy.
DEADLINE	This QoS policy states the maximum inter-arrival time spent in waiting.
LATENCY_BUDGET	The maximum acceptable latency is determined using the LATENCY_BUDGET policy.
OWNERSHIP	This QoS policy defines if the same instance can be updated using multiple DataWriter objects.
OWNERSHIP_STRENGTH	If multiple DataWriters can update a single data instance, then ownership power is determined by it.
LIVELINESS	LIVELINESS indicates whether an Entity is alive or not.
TIME_BASED_FILTER	The minimum time interval between the data samples is stated by it.
PARTITION	This policy establishes a conceptual partition between topics in the Global Data Space.
RELIABILITY	The degree of reliability rendered or obtained during data communication is specified by it.
TRANSPORT_PRIORITY	The transport priority of data sent by DataWriter Entities is defined by this QoS policy.
LIFESPAN	This QoS policy defines the period for the validity of the published data sample.
DESTINATION_ORDER	The sequential order of data samples at the Subscriber side is set by it.
HISTORY	This policy implies how the system will cache and communicate data samples.
RESOURCE_LIMITS	Memory allocation that can be adopted by the buffer system is determined by this policy.
ENTITY_FACTORY	The ENTITY_FACTORY policy governs if the creation of child entities are in an active state or not.
WRITER_DATA_LIFECYCLE	This policy controls the actions of DataWriter in compliance with the life cycle of data instances.
READER_DATA_LIFECYCLE	This policy controls the actions of DataReader in compliance with the life cycle of data instances.

The automation levels along with the tasks are discussed below:

- **Level 0**: This automation level (field-level) consists of sensors and actuators to accumulate data from the environment and perform an action respectively. Typical examples of sensors can be a temperature sensor, humidity sensor, soil moisture sensor, electric conductivity sensor, pH sensor, light sensor, thermal sensor, solar radiation sensor, barometric pressure sensor, carbon dioxide sensor, dissolved oxygen sensor, macro-mineral sensor, wind speed and direction sensor, air-quality sensor, RFID tags, weight sensors, etc. Actuators can be sprayers, linear actuators such as stepper motors, spreader actuators to spread fertilizers and pesticides, electric motors, hydraulics.
- **Level 1**: Control level where machines have PLC, or proportional–integral–derivative (PID) integrated into them. In a typical factory environment, this could be a single production line. In our case, a single Zone Controller (ZC) is placed within a farming zone to control and perform a particular function. For example, a ZC used to control the temperature in a greenhouse farm.
- **Level 2**: This supervisory (process control) level functions to synchronize and control all machines or production lines in an integrated manner. A process management system, such as SCADA, is used to monitor and control multiple systems in real-time. The Farm Controller (FC) is used to gather data for analysis, monitor, and control in an automated manner. FC can manage multiple ZCs with the help of a graphical user interface (GUI) or Human-Machine Interface (HMI) remotely.
- **Level 3**: This Production Planning and Control level (PPC) comprises the manufacturing execution system (MES) that serves to control the planning and operations of the entire plant from raw materials to the finished product in real-time. PPC manages multiple FCs to work in a coordinated manner to achieve the target. Data gathered from lower levels are analyzed and help the actors for the decision-making process. This planning level ensures optimized productivity and cost by adjusting the system in real-time. An example in the agro-industry would be the management of multiple hydroponic farms that harvest different food products. Each product might need different environmental conditions to cultivate. Therefore PCC controls the activities related to only production of the intended product.
- **Level 4**: Enterprise Resource Planning (ERP) level is the management level in the industrial plant. The role of ERP is to maintain overall production planning via

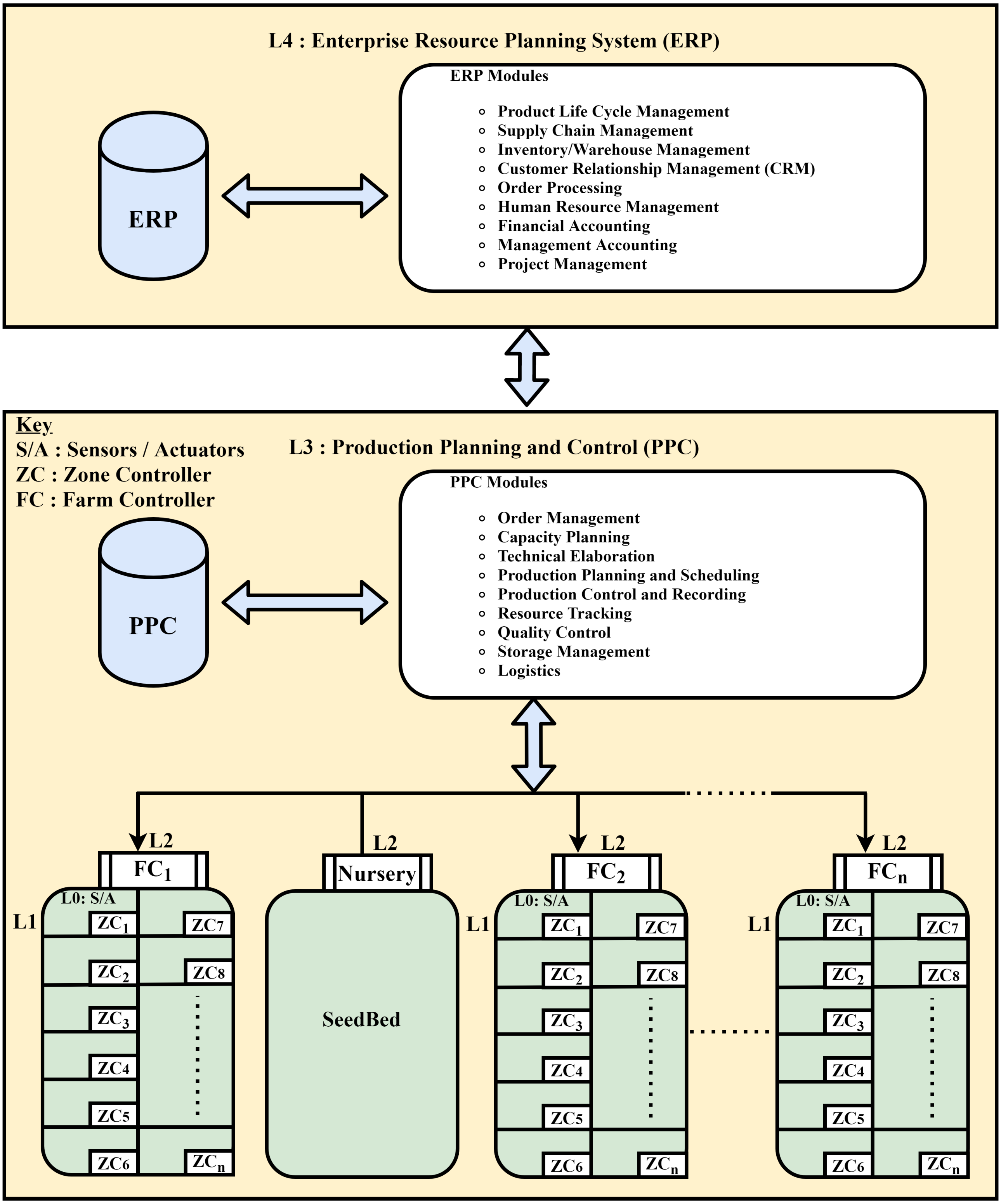

FIGURE 5. Proposed multimodal communication model in the agro-industry.

the ERP system. It deals with product life cycle management, supply chain management, and warehouse management, etc. ERP controls all activities, from production to distribution and consumption.

As discussed above, all the levels have distinct functions to be carried out along the supply chain. A high level of coordination might be necessary between each level to enhance productivity and quality, reduce the production cost, and

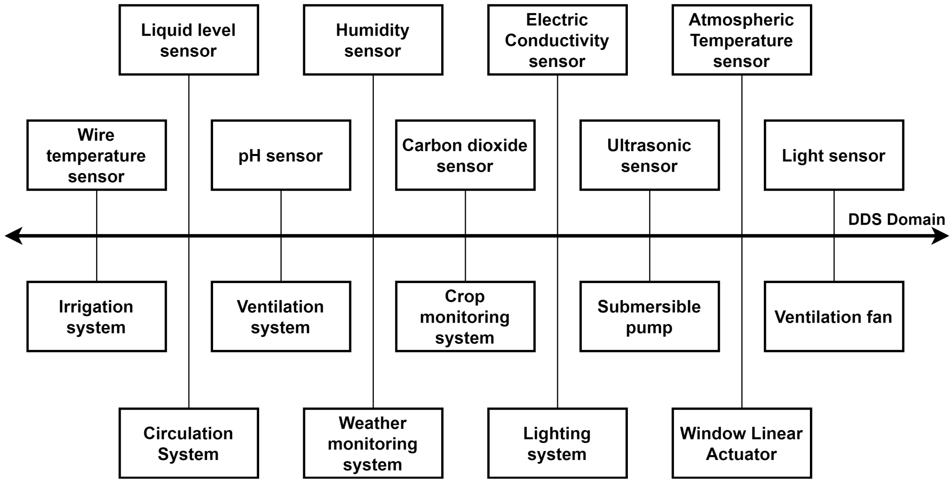

FIGURE 6. Reference architecture of the smart hydroponic farm case study.

to ensure sustainable production. Synchronization and integration are significant between automation levels to reduce the yield gap. Therefore, interoperability between modular production systems is of great importance. We propose to implement DDS middleware to enable the communication between these production systems in different automation levels. The production systems would act as Publishers or/and Subscribers. The integration of DDS middleware would make the system more flexible and adaptable to changes in real-time. Another advantage of using DDS middleware is the availability of a rich set of QoS policies that govern the communication between the systems. These QoS policies would impact the overall performance of the system and ensure efficient resource usage.

A. CASE STUDY ILLUSTRATION FOR THE EMPLOYMENT OF THE PROPOSED COMMUNICATION MODEL IN HYDROPONIC SYSTEMS

We represent a case study to describe and elaborate on the proposed communication model in the context of smart agriculture. Nowadays, farm producers are shifting towards hydroponic systems. Hydroponic systems have more efficient water utilization with an increase in production confined in a limited dense space. Also, crops are grown faster in a well-controlled hydroponic system. These systems provide an opportunity to cultivate crops in an unfavorable environment. Therefore, we consider a smart hydroponic system to discuss our case study. Figure 6 illustrates the reference architecture for our case study. The hydroponic system components consist of several subsystems, sensors to measure the crop and environmental conditions, and actuators to control the environmental parameters. Each subsystem in the hydroponic system performs a particular function. For example, the circulation system monitors and controls the liquid flow in the system. Farming operations require multiple subsystems to integrate and coordinate among themselves. The lighting system, ventilation system, and irrigation system need harmonization to utilize water efficiently. Sensors are used to measure the temperature, humidity, light intensity, pH, nutrient level in the reservoir, electric conductivity, water quality, total dissolved salts (TDS), and carbon dioxide of the system. The sensor types, models, and their usages are shown in Table 3. The subsystems receive data from the sensors, check against a predefined threshold, and send control signals to the actuators. The actuators receive the control signals and execute commands to switch on or off the ventilation fan, submersible pump, or window linear actuator to reserve water.

Smart agriculture, more precisely smart hydroponic systems, are information-intensive systems that may have strict QoS requirements. Our proposed model follows a data-centric approach, and the isolation of individual components adds modularity to the system. Based on the reference architecture, we define our data model for the smart hydroponic system. We map the defined data model to the DDS domain, data types, and topics. The elements of the system are domain participant nodes that join or leave multiple DDS domains. These nodes can act as Publishers, Subscribers, or both. Each node can distinctly define information as topics. The updates of the topic instances, known as data samples, are exchanged between them. All communication between the components of the system is through the middleware. The auto-discovery mechanism of DDS middleware would allow any component to join or leave the DDS domain at any time. Therefore, integrating two or more components to coordinate and perform a particular operation is simple without the need for centralized control. The architecture, shown in figure 6, consists of six subsystems, nine sensors, and three actuators. The sensors are the Publishers that publish environmental conditions to the GDS. The subsystems act as both Publishers and Subscribers where it subscribes to the sensed data and publishes control data. The actuators are the Subscribers of the control data. In the perspective of our proposed multimodal communication model, we categorize the automation

TABLE 3. Sensor types, models and their usages in our case study.

Sensor Type	Sensor Model	Use
Wire temperature sensor	DS18B20	To measure the temperature of the nutrient solution
Liquid level sensor	VL53L0X	To estimate the level of liquid in the reservoir
pH sensor	E-201C	To measure the pH value of the liquid
Atmospheric temperature and humidity sensor	DHT11, DHT22	To measure the atmospheric temperature and humidity of the environment
Carbon dioxide sensor	CDM4161, MH-Z16	To monitor the carbon dioxide concentration of the surrounding
Electric conductivity sensor	DFR0300-H	To measure nutrients, salts or impurities concentration in the liquid; To assess the quality of water
Ultrasonic sensor	HC-SR04	To estimate the water or liquid level
Light sensor	TSL2561, BH1750	To monitor the light intensity

levels in an agro-industry environment. At level 0, the sensors and actuators exist to measure and control the local farming processes. The Zone Controllers (ZCs), at level 1, monitor the data and send control instructions to the actuators. Typical ZCs are the subsystems that manage the functions in a single farming zone. Microcontrollers connected to sensors and actuators can function as ZCs. At level 2, the Farm Controllers (FCs) regulate multiple subsystems to work in a coordinated manner. It receives the aggregated data from the ZCs and analyzes it for better decision making regarding the whole production process on a single farm. Single-board computers such as Raspberry Pi or BeagleBoard can function as FCs. At level 3, PPC operates multiple farms to ensure optimized productivity and cost by adjusting the system in real-time. ERP, level 4, maintains the overall production planning along the whole supply chain. With regards to the reference architecture, the subsystems make up the ZCs. The sensors and actuators connect to the ZCs. The FCs operate several ZCs to automate the hydroponic production. All communications within a single hydroponic plantation follow a publish-subscribe pattern using DDS middleware, ensuring modularity and reliability.

FIGURE 7. Small-scale hydroponic farm (front view).

VI. EXPERIMENTAL WORK

For our experimental work, we used single-board computers as FCs to set up on a small scale hydroponic farm. The dimensions of the hydroponic system are 10m long and 1m wide. Figure 7 and 8 exhibits the interior of the farm. The farm had five polyvinyl-chloride (PVC) pipes with hollows made for pots with Rockwool, a reservoir with a submersible pump, and a ventilation fan. The water flowed from the top to the bottom pipeline using the pump in a closed recirculation. The system components are the sensors, actuators, ZCs, and FCs. Sensors, such as temperature sensors, humidity sensors, and ultrasonic sensors, are used to measure and sense the environment. A submersible water pump and ventilation fan are the actuators of the hydroponic system. Figure 1 presents the schematic circuit diagram of the ZC. The sensors, actuators, and the WiFi module are interfaced to it, as seen in the figure. The ZCs transmit the aggregated data to the FCs, which in this scenario are the single-board computers. The FC target machines were Raspberry Pi 3 Model B+, and we checked the feasibility and performance of the proposed system against a system that uses plain sockets. The ZCs and FCs would act as both Publisher and Subscriber and communicate via DDS middleware. The purpose of the experiment was to analyze the system performance using DDS standard middleware for data communication.

Assuming the channel is error-free, we will evaluate the system in terms of throughput, average latency, and packet delivery ratio (PDR) as performance metrics. The QoS policies used for our research are as follows:

FIGURE 8. Small-scale hydroponic farm (back view).

- **RELIABILITY**: This policy indicates the extent of reliability the system can provide or receive. There are two kinds, RELIABLE or BEST_EFFORT. For RELIABLE kind, the Publisher will continue sending data until all the data is completely received by the Subscriber. For BEST_EFFORT, the Publisher will not resend data in case of failure.
- **HISTORY**: Defines how the system will buffer data and send data gradually. KEEP_LAST and KEEP_ALL with depth as optional are the two kinds. KEEP_ALL kind stores all the data in the buffer, whereas KEEP_LAST stores the latest data with depth=1 as the default values.
- **DURABILITY**: Specifies how long the data can exist after being written. There are four kinds, namely VOLATILE, TRANSIENT, TRANSIENT_LOCAL, and PERSISTENT. VOLATILE indicates that no samples of data are kept. TRANSIENT means data is stored in memory. TRANSIENT_LOCAL keeps data in local memory and is associated with the DataWriter. For PERSISTENT, data is kept on permanent storage.
- **PRESENTATION**: Two Boolean, coherent_access and ordered_access, control how the data is represented to the Subscriber. Coherent_access if true represents the set of changes as a unit to the Subscriber. Ordered_access represents the changes in order as occurred in the Publisher.
- **RESOURCE_LIMITS**: This policy states the amount of resources that can be consumed. It is defined by the integer variable max_samples and max_samples_per_instance. The default value is set to LENGTH_UNLIMITED.

TABLE 4. QoS policy parameters defined for the experimental work.

QoS policy	Parameter value
RELIABILITY	RELIABLE
HISTORY	KEEP_ALL
DURABILITY	VOLATILE
PRESENTATION	ordered_access = true
RESOURCE_LIMITS	max_samples=10000, max_samples_per_instance=10000

Table 4 denotes the parameter values set for each QoS policy for our experimental work. We run the hydroponic system for two weeks to collect and model the network traffic of the system. We use D-ITG (Distributed Internet Traffic Generator) [118] to generate the modeled network traffic. We vary the payload size (data sample size) in bytes for the system and measure the throughput, average latency, and PDR with and without DDS middleware. Another extended QoS policy feature of DDS is BATCH to reduce transmission overhead associated with reliable communication. We examine the effect of batching on the throughput of the system.

VII. RESULTS AND DISCUSSION

In this section, we discuss the performance results of our experimental work. Our research aims to measure the system performance with DDS middleware integrated for reliable communication between production systems in a heterogeneous environment. We compare these results with the system with no DDS implemented, i.e., communication via UDPv4 sockets. Furthermore, we observe the effect of batching on the throughput. The throughput is measured by the average rate of successful data messages delivered in a given time. Figure 10 presents the throughput graph against varying payload sizes for our proposed DDS system and system without DDS middleware (UDPv4 sockets). There is a linear increase in throughput for packet size more than 32 bytes until it saturates at 8192 bytes, as seen in the figure. For payload size greater than 8192 bytes, the throughout saturates around 95 Mbps for both systems. The maximum bandwidth supported by the network interface controller (NIC) of FCs is 100 Mbps. Therefore, the throughput increases with an increase in payload sizes until it reaches maximum network utilization at around 95% for both systems.

Referring to [36], [38], we will look more closely at throughput results for payload size between 32 and 1024 bytes. Table 5 exhibits the throughput results obtained from the experimental work. From figure 11, we can view the graphical representation of the throughput results. The system using DDS middleware and no BATCH QoS policy for communication has a linear increase in throughput. However, a system using plain sockets performs better than using DDS middleware. The gap between the throughput values of both systems increases with increasing payload size. The difference in the throughput values is highest at 512 bytes. A significant improvement in the throughput is observed with the use of the BATCH QoS policy. Batching aggregates the

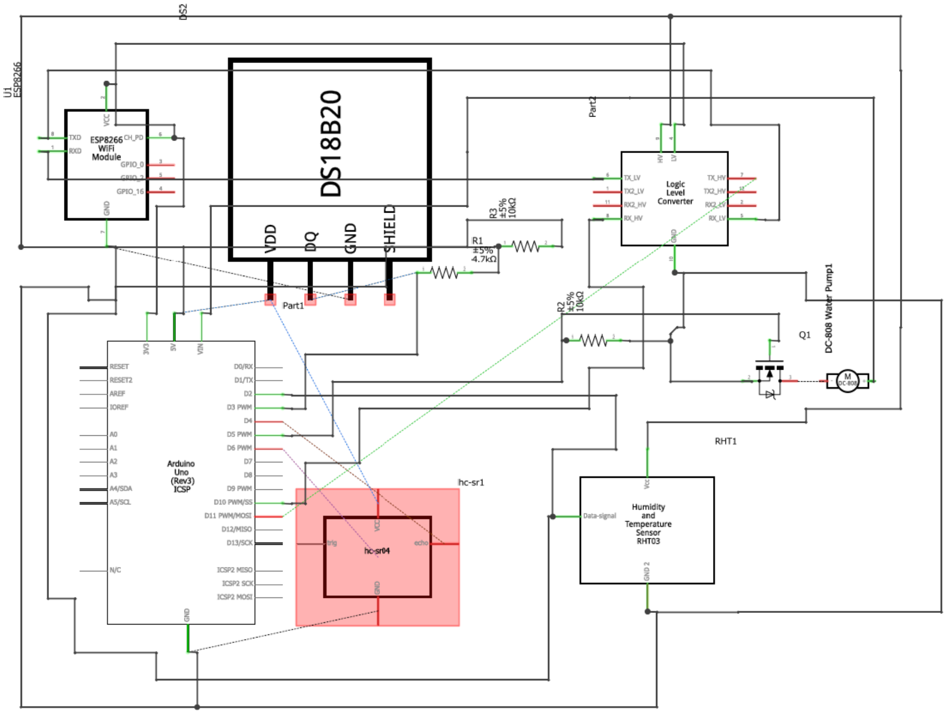

FIGURE 9. Schematic circuit diagram of the Zone Controller (ZC).

TABLE 5. Throughput values attained from the experimental works.

	Throughput (Mbps)		
Payload Size (bytes)	System without DDS	Proposed DDS system	Proposed DDS system (Batch QoS)
32	6.4	1.8	26.1
64	11.6	3.4	43.3
128	23.8	6.8	80.1
256	46.5	13.6	83.6
512	82.1	23.2	87.1
1024	91.7	44.1	91.8

TABLE 6. Latency values achieved from the experimental works.

	Average latency (microseconds)	
Payload Size (bytes)	System without DDS	Proposed DDS system
32	357	632
64	370	633
128	386	670
256	419	709
512	485	796
1024	608	926

TABLE 7. Packet delivery ratio (PDR) values obtained from the experimental works.

	Packet Delivery Ratio	
Payload Size (bytes)	System without DDS	Proposed DDS system
32	1	1
64	1	1
128	1	1
256	0.97	1
512	0.99	1
1024	0.98	1

data samples into a single data packet specified by the batch size parameter. When packet size is less than 1024 bytes, the throughput of our proposed system with BATCH QoS policy is higher. Therefore, using our proposed model for communication would be more efficient.

Average latency denotes the time required by the data samples to reach the Subscriber from the Publisher. Table 6 presents the average latency values in microseconds incurred by the system. Figure 12 graphically illustrates the average latency values attained for varying payload sizes. The average latency increases linearly with increasing payload size. We can observe that our proposed DDS system has suffered higher average latency than the system using plain sockets for communication for any payload size. The difference in the average latency values of the two systems is constant for varying payload sizes. The added average latency for using DDS middleware to communicate between systems is approximately 235 microseconds. This added latency is due to the inclusion of additional logic to send or receive data

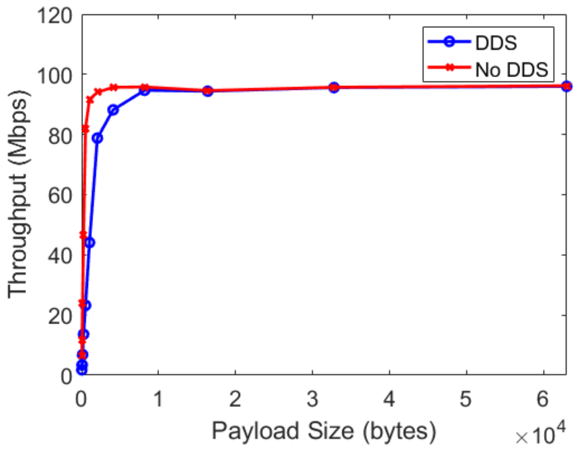

FIGURE 10. The figure presents the throughput of the proposed DDS system compared against system without DDS implemented with varying payload size.

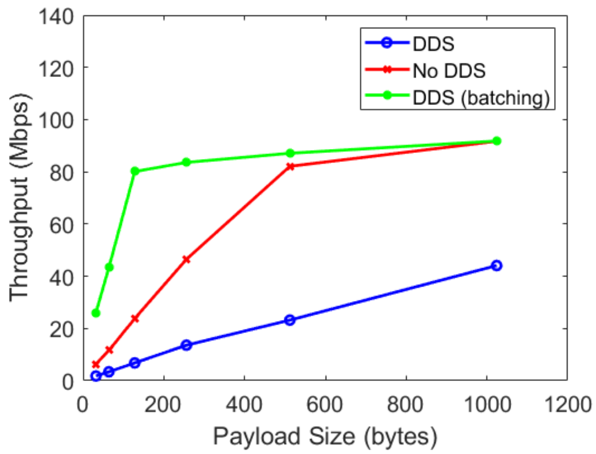

FIGURE 11. The figure shows the throughput of the proposed DDS system compared against system without implementation of DDS and the use of BATCH QoS policy.

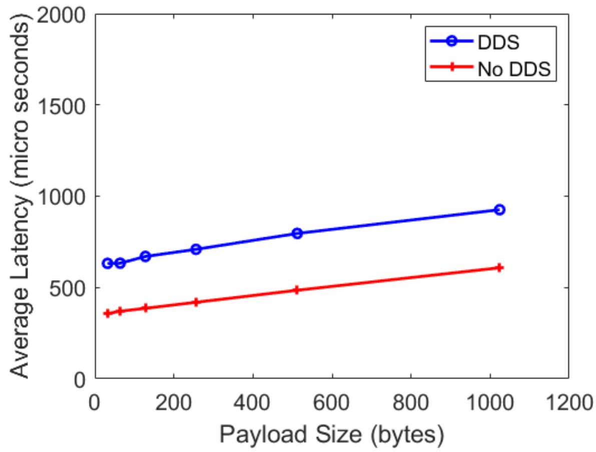

FIGURE 12. The figure displays the latency of the proposed DDS system compared against system without implementation of DDS.

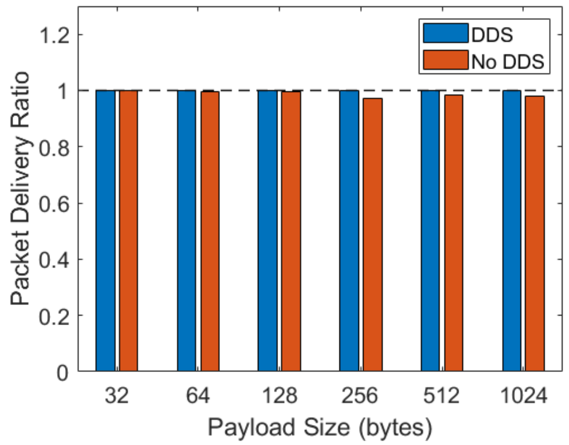

FIGURE 13. The figure exhibits the Packet Delivery Ratio (PDR) of the proposed DDS system compared against system without implementation of DDS.

through the DDS middleware. Although the application of batching increases throughput, the system incurs a minimum latency of 235 microseconds.

PDR indicates a ratio of the total number of received data to the total number of sent data. PDR equals one if all the data is received by the Subscriber successfully. PDR less than one indicates lost or dropped packets in the system. Table 7 shows the calculated PDR values for both systems. The graph in figure 13 displays the PDR values for varying payload sizes. For our proposed model, PDR values remain 1 for any payload size. The system using sockets has PDR less than 1 for packet sizes 128, 256, and 1024 bytes. The highest number of packets lost is when the payload size was 256 bytes resulting in a PDR value of 0.97. PDR values for a system with no DDS implemented (UDPv4 sockets) are less than 1 when payload sizes are more than 128 bytes indicating dropped data packets. Hence system using DDS middleware for communication ensures reliability.

VIII. CONCLUSION

The incorporation of Industry 4.0 technologies in the agricultural domain will transform the agro-industry significantly. The adoption of new technologies and strategies will enhance productivity and reduce the yield gap to satisfy the market demand of the growing population. Agriculture 4.0 approaches can tackle the challenges of agricultural supply chain management, but managing production, planning, and control are difficult due to the high mobility of production systems. Production systems use a distributed integration approach due to its advantages such as resource sharing, scalability, fault tolerance, etc. Nevertheless, manageability and system integration can be highly complex if the modular production systems are heterogeneous. We propose a multimodal communication model that utilizes DDS middleware to integrate production systems for interoperability between multi-vendor production lines. The research conducted suggests that DDS integrated systems can reliably communicate with each other in real-time, but incur additional latency due to the discovery mechanism. Furthermore, the throughput of the DDS integrated system improves with the use of batching. Based on our findings, our recommendation would be to design and integrate production systems with DDS middleware to reach maximum network throughput with minimum expected latency ensuring reliability.

FUTURE SCOPE

The Green Revolution was directed towards sustainable development in the agricultural sector with the support of global policy-makers. Modern farming practices that use AI, big data analysis, robotics, and machine learning plays a vital role in the advancement of Agriculture 4.0 to increase the productivity and eco-efficiency of agricultural value creation. For future work, we tend to analyze how tuning the QoS policies might affect the performance in a large-scale farm while considering the energy consumption. We aim to develop an ad-hoc printed circuit board (PCB) of the Zone Controller for minimizing the total cost of deployment. Also, we will consider studying the security aspects of the integration of DDS middleware in production systems. Additionally, employing machine learning algorithms in agricultural supply chains and the adoption of 5G technologies can be considered for future work.

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